REMARKS

Entry of this amendment, reconsideration of all grounds of objection and rejection, and allowance of all the pending claim are respectfully requested. Claim 5-8 and 12-14 are pending herein. Claims 5 and 12 are independent claims. Claim 7 has been amended to overcome the rejection thereto in the Office Action.

Claims 5-8 and 12-14 stand rejected under 35 USC § 112, first paragraph, as failing to comply with the enablement requirement. Applicant respectfully requests withdrawal of this ground of rejection for the reasons indicated herein below.

Applicant respectfully submits that the recitation regarding the SOA is fully enabled by the specification. A semiconductor optical amplifier described in the present invention performs generally the optical amplifying function. However, according to the physical properties, the semiconductor optical amplifier (SOA) can perform the optical detection function within the linear area, such as the laser diode (LD), and can perform the optical detection function within the nonlinear area, such as the photodiode (PD).

Especially, the bias current is controlled in order to perform selectively the operation of the above LD or PD. Herein, the description regarding FIG. 4 (particularly at page 15, lines 5 to page 16, line 7, and modulation by the SOA disclosed at page 15, lines 20-22) exemplifies the change of the operational area according to the above bias current.

In other words, on the gain characteristics curve line shown in FIG. 4, the SOA performs the optical modulation function within the linear area having the linear feature on the basis of the predetermined threshold current (T), whereas the SOA performs the

optical detector function within the absorption area having the nonlinear feature.

In addition, Applicant has attached hereto, U.S. Patent 5,289,480 entitled "Triple Function Semiconductor Laser Amplifier" by Koai *et al.*, which issued in 1994, and clearly states in the Abstract "a semiconductor laser amplifier that provides for simultaneous detection, amplification and modulation of an input optical signal" (emphasis in underlining added). FIG. 1 of Koai shows an SLA 110 (which is another term in the art for SOA, please see U.S. Patent 6,738,187 to DeCusatis *et al.* (the pertinent page provided therewith)). The symbol 110 in Koai *et al.* is known in the art and does not utilize any special connotation to depict simultaneous functions of an SOA. Please see column 2, lines 42-45 of Koai *et al.*

Accordingly, Applicant respectfully traverses the rejection in the Office Action wherein it is alleged that a person of ordinary skill in the art, from the block diagram in FIG. 3 showing an SOA 220, would not know or understand how to operate an Access Point according to the present claims, which includes an SOA having simultaneous functions.

Furthermore, in the response to previous arguments, the Office Action appeared to indicate that the use of the term semiconductor optical amplifier (SOA), without anything more, would not be enabling in the claims. However, Applicant respectfully submits U.S. 5,289,480, which is proof that it within the level of ordinary skill in the art for a simultaneous function SOA to be used without special reference or terminology.

In addition to the above-identified patent presented to show that a person of ordinary skill in the art would understand that a semiconductor optical amplifier can perform simultaneous multiple functions, and the documents Applicant has previously

provided documentation regarding SOAs and their capabilities, Applicant further introduces a paper written by Doctor M.J. Connelly, Senior Researcher in Electronic Engineering and Group Leader of the Optical Communications Research Group in the Department of Electronic and Computer Engineering, University of Limerick, Ireland.

The enclosed paper, entitled, 'Semiconductor Amplifiers and Their Applications' (Invited paper), *OPTOEL'03*, Madrid, Spain, July 2003, (also available on the Internet at http://www.uc3m.es/uc3m/dpto/IN/dpin08/Semiconductor_optical_amplifiers.pdf), which discloses SOAs (Dr. Connelly uses the term "SOA" and nothing more) used for modulation (please see page 3, sections 4a-4c) notes that SOAs can have at least four types of nonlinearity, including cross gain modulation (XGM), cross phase modulation (XPM), self-phase modulation (SPM) and four-wave mixing (FWM). The paper also discloses wavelength conversion (page 4), switching (Section 5b) and other functions. While Applicant respectfully submits that the present invention is not limited to the examples shown and discussed in the materials presented to the Examiner to traverse the rejection under 35 U.S.C.§112, first paragraph, Applicant has shown that a person of ordinary skill in the art is aware of multi-function simultaneous functioning SOAs, without further detailed explanation being required in the specification. Applicant respectfully submits that a while a patent application must be enabling (and this application is enabling to a person of ordinary skill in the art), the application is written so as not to obscure the invention with background that is known in the art. Applicant's claimed invention is an Access Point that includes an SOA that can perform multi-functions simultaneously, and not an SOA itself.

Accordingly, Applicant has traversed the rejection under 35 U.S.C.§112, first

paragraph and respectfully requests withdrawal of this ground of rejection.

For all the foregoing reasons, it is respectfully submitted that all the present claims are patentable in view of the cited references. A Notice of Allowance is respectfully requested.

Should the Examiner deem that there are any issues which may be best resolved by telephone communication, please contact Applicant's undersign representative at the telephone number listed herein below.

Respectfully submitted,

Date: 8/9/07

By: Steve S. Cha
Attorney for Applicant
Registration No. 44,069

Enclosures:
U.S. Patent 5,289,440
Page from U.S. Patent 6,738,187
Article by M.J. Connelly

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SC/sg

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Steve Cha, Reg. No. 44,069
(Name of Registered Rep.)

8/9/07
(Signature and Date)

US005289480A

United States Patent [19]

Koai et al.

[11] Patent Number: 5,289,480

[45] Date of Patent: Feb. 22, 1994

[54] TRIPLE-FUNCTION SEMICONDUCTOR LASER AMPLIFIER

[75] Inventors: Kwang-Tsai Koai, Concord; Robert Olshansky, Wayland, both of Mass.

[73] Assignee: GTE Laboratories Incorporated, Waltham, Mass.

[21] Appl. No.: 13,505

[22] Filed: Feb. 3, 1993

[51] Int. Cl.[5] H01S 3/00

[52] U.S. Cl. 372/38; 372/26; 372/29; 372/31

[58] Field of Search 372/38, 26, 29, 31

[56] References Cited

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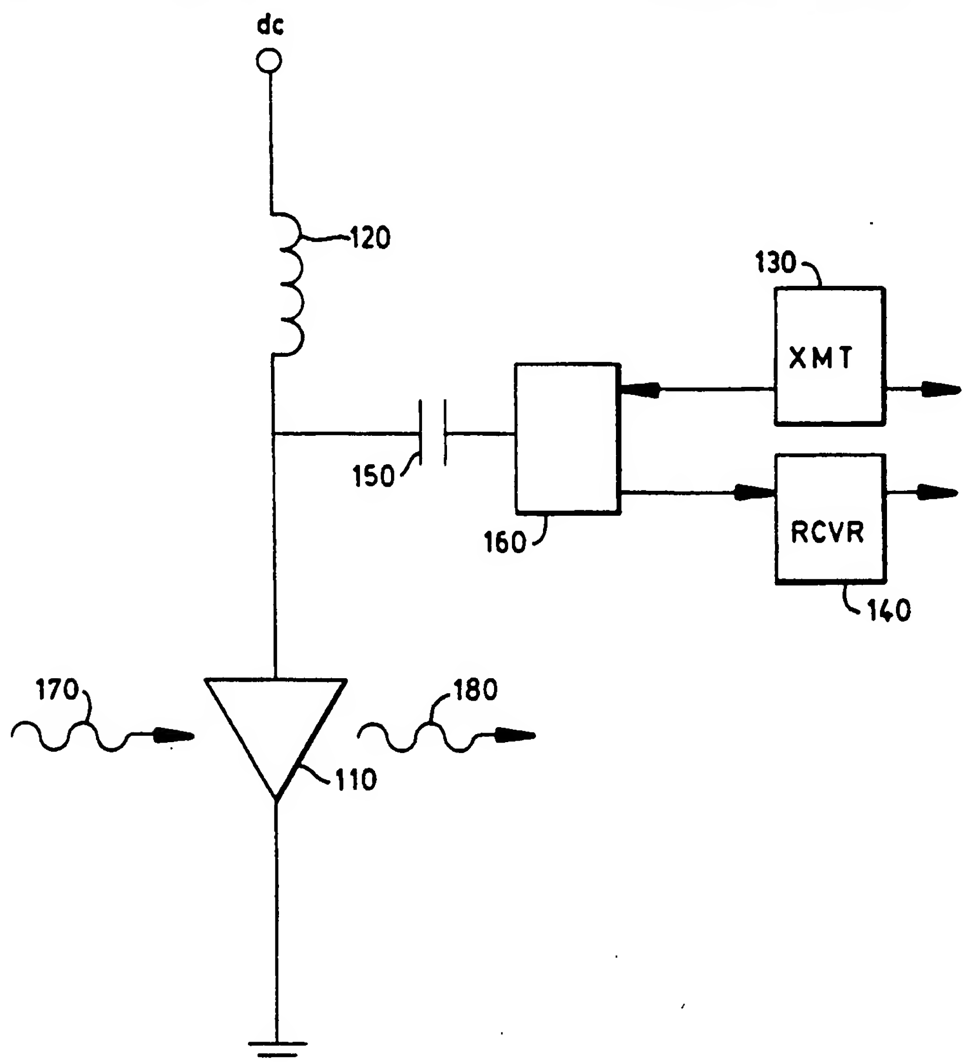
Primary Examiner—Georgia Y. Epps

Attorney, Agent, or Firm—Lawrence E. Monks

[57] ABSTRACT

An optoelectronic device is disclosed utilizing a semiconductor laser amplifier that provides for simultaneous detection, amplification, and modulation of an input optical signal. In one embodiment, an electronic transmitter and receiver are coupled to the semiconductor laser amplifier through an RF circulator. In an alternative embodiment, the electronic transmitter and receiver are coupled to the semiconductor laser amplifier through an RF power splitter with frequency or phase discriminating circuitry.

5 Claims, 2 Drawing Sheets



US006738187B2

(12) **United States Patent**
DeCusatis et al.

(10) **Patent No.: US 6,738,187 B2**
(45) **Date of Patent: May 18, 2004**

(54) **SEMICONDUCTOR OPTICAL AMPLIFIERS USING WAVELENGTH LOCKED LOOP TUNING AND EQUALIZATION**

(75) Inventors: **Casimer Maurice DeCusatis**, Poughkeepsie, NY (US); **Lawrence Jacobowitz**, Wappingers Falls, NY (US)

(73) Assignee: **International Business Machines Corporation**, Armonk, NY (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 462 days.

(21) Appl. No.: **09/893,043**

(22) Filed: **Jun. 27, 2001**

(65) **Prior Publication Data**

US 2003/0002141 A1 Jan. 2, 2003

(51) **Int. Cl.**[7] **H01S 3/00**
(52) **U.S. Cl.** **359/344**; 359/337
(58) **Field of Search** 359/344, 337

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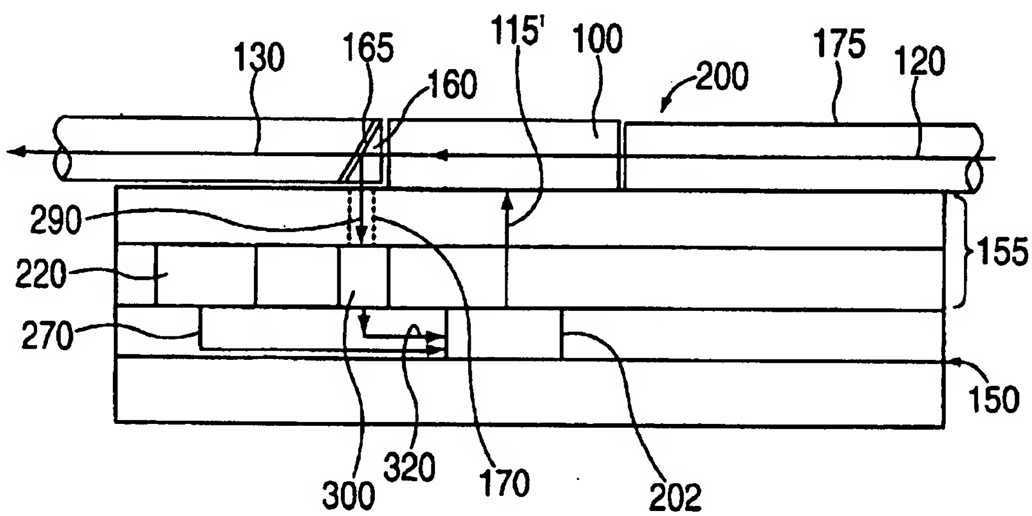
Primary Examiner—Mark Hellner
(74) *Attorney, Agent, or Firm*—Scully, Scott, Murphy & Presser; Tiffany L. Townsend, Esq.

(57) **ABSTRACT**

A system and method for improving optical signal gain efficiencies of semiconductor optical amplifier devices. The system and method exploits a wavelength-locked loop servo-control circuit and methodology that enables real time mutual alignment of the center wavelength of an optical signal having a peaked spectrum function and transmitted through the semiconductor optical amplifier, and a center wavelength of a wavelength selective device such as an optical filter implementing a peaked passband function in an optical system. The wavelength-locked loop servo-control circuit and methodology may be further exploited to control various types of modulation applied to the optical signals transmitted in optical systems.

38 Claims, 8 Drawing Sheets



SEMICONDUCTOR OPTICAL AMPLIFIERS USING WAVELENGTH LOCKED LOOP TUNING AND EQUALIZATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to optical devices such as lasers, and fiber optic data transmission systems employing the same, and particularly to a novel wavelength-locked loop servo-control circuit for optimizing performance of semiconductor optical amplifiers.

2. Description of the Prior Art

Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) are light-wave application technologies that enable multiple wavelengths (colors of light) to be paralleled into the same optical fiber with each wavelength potentially assigned its own data diagnostics. Currently, WDM and DWDM products combine many different data links over a single pair of optical fibers by re-modulating the data onto a set of lasers, which are tuned to a very specific wavelength (within 0.8 nm tolerance, following industry standards). On current products, up to 32 wavelengths of light can be combined over a single fiber link with more wavelengths contemplated for future applications. The wavelengths are combined by passing light through a series of thin film interference filters, which consist of multi-layer coatings on a glass substrate, pigtailed with optical fibers. The filters combine multiple wavelengths into a single fiber path, and also separate them again at the far end of the multiplexed link. Filters may also be used at intermediate points to add or drop wavelength channels from the optical network.

Optical communication links in systems employing WDM or, optical networks in general, require amplification to extend their distances. For example, optical signal amplification are needed in optical links for applications such as disaster recovery in a storage area network or parallel sysplex. There are many types of amplifiers, however, for some wavelength ranges of interest, semiconductor optical amplifier devices (SOAs) have emerged as being extremely useful. An SOA functions much like an in-line semiconductor laser diode in that it is optically pumped for amplifying incoming optical signals without requiring optical/electrical conversions. However, the SOA also broadens the optical spectrum of the amplified light, which may induce undesired effects such as dispersion and modal noise that limit the effectiveness of this technology.

Particularly, as illustrated in FIG. 1, the basic SOA device **100** (also known as a semiconductor laser amplifier or "SLA") is very similar in construction to a Fabry Perot semiconductor laser diode, comprising semiconductive layers **110, 111** and an active layer **112** forming an optical cavity which receives an input optical signal **120**. Generally, when an electrical current **115** is pumped through the device, electrons are excited in the optical cavity **112** to effect gain of the input signal **120** in the direction of propagation. The output optical signal **130** is thus an amplified version of the input signal. It is understood that mirrors may be implemented in the optical cavity for increasing the effective path length through the gain medium, and hence increase the overall gain. The SOA offers potential advantages over other optical amplification technologies such as doped fiber amplifiers. In particular, the SOA can be monolithically integrated with other semiconductor devices on a common chip or substrate, e.g., GaAs or hybrid Si on insulator, and mass

produced at low cost. SOAs can easily amplify light at various wavelengths, including 1300 nm and 850 nm which is a unique feature, since erbium doped fiber amplifiers (EDFAs) operate only at wavelengths near 1550 nm, and more exotic doped fiber amplifiers at other wavelengths are more expensive and difficult to manufacture. This is an important advantage, as the SOA is a low cost solution to amplify the 1300 nm and 850 nm windows most commonly used in data communication systems such as ESCON, Fibre Channel, and Gigabit Ethernet. The SOA is also a very compact and highly reliable device. However, an SOA differs from a laser diode in that the SOA operates below the threshold current required for laser action. (In a variant design, the traveling wave SOA, may be operated above threshold but has other design and manufacturing problems which have so far prevented its becoming a commercially available device). Due to this, the light emerging from an SOA has a very broad spectral width, around 20–50 nm and, in some cases, several hundred nanometers, as opposed to a typical narrowband laser which has about 2–3 nm spectral width. Thus, an optical signal entering the SOA will be amplified, but suffers a significant spectral broadening; the additional optical power is spread across a much wider frequency range. Not only is this an inefficient way to amplify the light, but the spectral broadening causes secondary effects such as increased dispersion, modal noise, and mode partition noise on the communication link; these noise sources can exhibit a noise floor, which means that the noise limits the maximum link distance regardless of the strength of the amplified signal. For this reason, SOAs have not been widely deployed in very long distance links, although they have found applications in shorter data and telecommunication systems.

Furthermore, if the SOA is operated at higher voltages or currents (still below threshold), the gain increases and the spectral broadening becomes worse. In principle, the SOA output may be optically filtered with a narrow band element such as an array waveguide grating or multilayer thin film interference filter, as these devices can be integrated onto the semiconductor substrate. However, such filters are very difficult to fabricate with their center wavelength exactly aligned to the peak of the SOA output spectrum, hence they have unacceptably high insertion loss (up to several dB) which cancels out the gain of the optical amplifier. Further complicating the problem, the SOA tends to have a high insertion loss, as well as high spontaneous emission noise due to random generation of photons at the amplified wavelengths. The SOA spectrum also drifts with changes in temperature or bias voltage, as well as with the aging of the SOA diode.

It would thus be highly desirable to provide a system and method for automatically compensating for the undesirable effects of an SOA, and particularly a system and method for overcoming the spectral broadening associated with SOA devices.

It would thus be highly desirable to provide a servo-control feedback loop for stabilizing the SOA output and tracking the center wavelength of the amplified signal to the peak of an optical filter passband with high accuracy to enable higher gains than currently achievable with SOAs.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a system and method for overcoming the spectral broadening associated with semiconductor optical amplifier (SOA) devices.

(1)

Semiconductor Optical Amplifiers and their Applications

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Key words. Semiconductor optical amplifier, optical communication systems.

1. Introduction.

There has been rapid growth in the deployment and capacity of optical fibre communication networks over the past twenty-five years. This growth has been made possible by the development of new optoelectronic technologies that can be utilised to exploit the enormous bandwidth of optical fibre. Today, systems are operational which operate at bit rates in excess of 100 Gb/s. Optical technology is the dominant carrier of global information. It is also central to the realisation of future networks that will have the capabilities demanded by society. These capabilities include virtually unlimited bandwidth to carry communication services of almost any kind, and full transparency that allows terminal upgrades in capacity and flexible routing of channels. Many of the advances in optical networks have been made possible by the optical amplifier.

Optical amplifiers can be divided into two classes: optical fibre amplifiers (OFA) and semiconductor optical amplifiers (SOAs). The former has tended to dominate conventional system applications such as in-line amplification used to compensate for fibre losses. However, due to advances in optical semiconductor fabrication techniques and device design, the SOA is showing great promise for use in evolving optical communication networks. It can be utilised as a general gain element but also has many functional applications including an optical switching and wavelength conversion. These functions, where there is no conversion of optical signals into the electrical domain, are required in transparent optical networks

This paper reviews SOA technology and the applications of SOAs in emerging optical communication networks.

2. SOA basics.

A schematic diagram of an SOA is shown in Fig. 1. The device is driven by an electrical current. The active region in the device imparts gain, via stimulated emission, to an input signal (Fig. 2). The output signal is accompanied by noise. This additive noise, amplified spontaneous emission (ASE), is produced by the amplification process. A comparison between OFAs and SOAs is given in Table 1.

SOAs are polarisation sensitive. This is due to a number of factors including the waveguide structure and the gain material. Polarisation sensitivity can be improved by the use of square-cross section waveguides and strained quantum-well material.

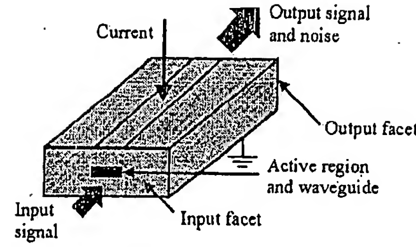

Fig. 1: Schematic diagram of an SOA.

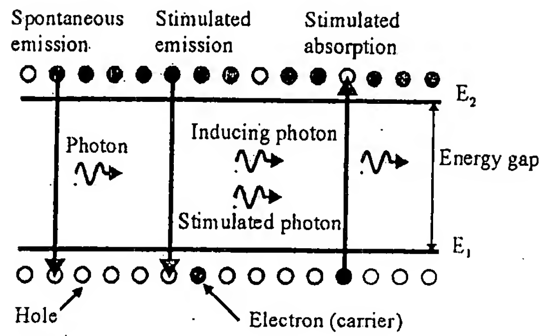

Fig. 2: Spontaneous and stimulated processes in a two level system.

Feature	OFA	SOA
Maximum internal gain (dB)	30 - 50	30
Insertion loss (dB)	0.1 - 2	6 - 10
Polarisation sensitive?	No	Weak (< 2 dB)
Pump source	Optical	Electrical
3 dB gain bandwidth (nm)	30	30 - 50
Nonlinear effects	Negligible	Yes
Saturation output power (dBm)	10 - 15	5 - 20
Noise figure (dB)	3 - 5	7 - 12 dBm
Integrated circuit compatible?	No	Yes
Functional device possibility?	No	Yes

Table 1: Comparison between OFAs and SOAs.

The gain of an SOA is influenced by the input signal power and internal noise generated by the amplification process. As the input signal power increases the gain decreases as shown in Fig. 3. This gain saturation can cause significant signal distortion. It can also limit the gain achievable when SOAs are used as multichannel amplifiers in wavelength division (WDM) multiplexed systems.

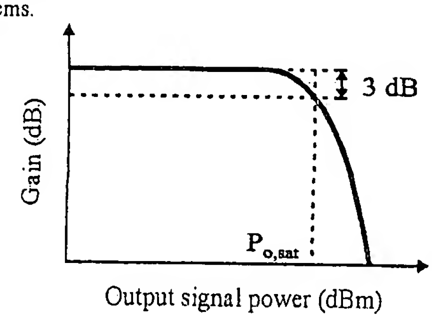

Fig. 3: Typical SOA gain versus output signal power.

SOAs are normally used to amplify modulated light signals. If the signal power is high then gain saturation will occur. This would not be a serious problem if the amplifier gain dynamics were a slow process.

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However in SOAs the gain dynamics are determined by the carrier recombination lifetime (few hundred picoseconds). This means that the amplifier gain will react relatively quickly to changes in the input signal power. This dynamic gain can cause signal distortion, which becomes more severe as the modulated signal bandwidth increases. These effects are even more important in multichannel systems where the dynamic gain leads to interchannel crosstalk. This is in contrast to optical fibre amplifiers, which have recombination lifetimes of the order of milliseconds leading to negligible signal distortion.

SOAs also exhibit nonlinear behaviour. These nonlinearities can cause problems such as frequency chirping and generation of intermodulation products. However, nonlinearities can also be of use in using SOAs as functional devices such as wavelength converters.

3. Basic network applications.

The principal applications of SOAs in optical communication systems can be classified into three areas: (a) Postamplifier or booster amplifier to increase transmitter laser power, (b) in-line amplifier to compensate for fibre and other transmission losses in medium and long-haul links and (c) preamplifier to improve receiver sensitivity (Fig. 4). The incorporation of optical amplifiers into optical communication links can improve system performance and reduce costs. The main requirements of optical amplifiers for such applications are listed in Table 2.

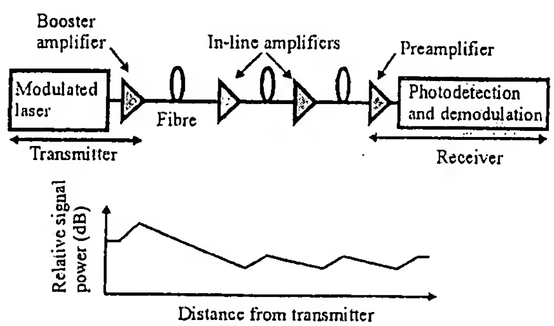

Fig. 4: Application of SOAs as booster amplifier, in-line amplifiers and preamplifier in an optical transmission link.

3.a. – Booster amplifier.

The function of a booster amplifier is to increase a high power input signal prior to transmission. The principle applications of booster amplifiers are listed in Table 3. Boosting laser power in an optical transmitter enables the construction of medium-haul links with increased transmission distance. Such links simply consist of an optical fibre between the transmitter and receiver. As this involves no active components in the transmission link, reliability and performance are improved.

In long-haul links the use of a booster amplifier can increase the link power budget and reduce the number of in-line amplifiers or regenerators required. Booster amplifiers are also useful in distribution networks (Fig. 5), where there are large splitting losses or a large number of taps. Booster amplifiers are also needed when it is required to simultaneously amplify a number of input signals at different wavelengths, as is the case in WDM transmission.

	Post-amp	In-line amp	Preamp
High gain	Yes	Yes	Yes
High saturation output power	Yes	Yes	Not critical
Low noise figure	Not critical	Yes	Yes
Low polarisation sensitivity	Not critical	Yes	Yes
Low insertion loss	Not critical	Yes	Yes
Optical filter	Not necessary	Not critical	Yes
Optical isolators	Yes	Not critical	Not critical

Table 2: Optical amplifier requirements.

Increase medium-haul optical transmission link distance
Increase long-haul optical transmission link power budget
Compensate for splitting and tap losses in optical distribution networks
Simultaneous amplification of WDM signals

Table 3: Applications of optical booster amplifiers.

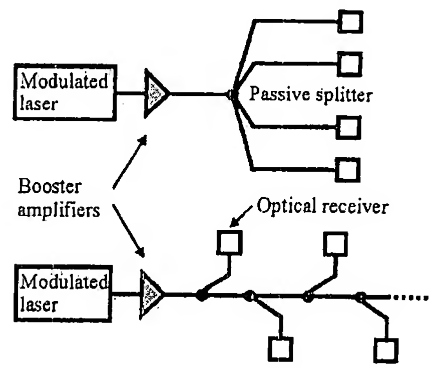

Fig. 5: Booster amplifier application in optical distribution networks.

3.b. – Preamplifier.

The function of an optical preamplifier is to increase the power level of an optical data signal beforeto detection and demodulation. The increase in power level can increase receiver sensitivity. This allows longer unrepeatered links to be constructed. A schematic diagram of a preamplified optical receiver is shown in Fig. 6. The receiver consists of an optical preamplifier, a narrowband optical filter and photodiode followed by post-detection circuitry and a decision circuit.

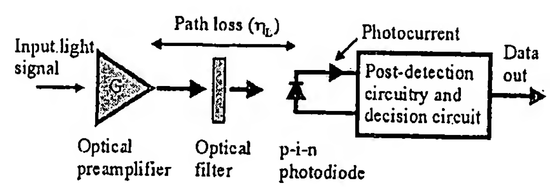

Figure 6: Preamplified optical receiver.

3.c. – In-line amplifier.

In loss limited optical communication systems, in-line optical amplifiers can be used to compensate for fibre loss thereby overcoming the need for optical regeneration. The main advantages of in-line SOAs are: Transparency to data rate and modulation format (unsaturated operation and at high bit rates), bidirectionality, WDM capability, simple mode of operation, low power consumption and

compactness. The latter two advantages are important for remotely located optical components.

3.d. – Transmission experiment

An example of a WDM transmission experiment is shown in Fig. 7 [2]. The transmitter consists of eight lasers combined by an 8:1 coupler. The wavelengths are in the range 1558-1570 nm with a channel spacing of 200 GHz. The channels are externally modulated at 20 Gbit/s. Three booster SOAs are used to compensate for the coupler and modulator losses. The transmission link is comprised of four amplified 40 km single-mode fibre links including dispersion compensating fibre. The span loss is 13 dB. The 12 to 14 dB of gain available from each amplifier is adequate to compensate for the link loss. The receiver consists of two SOA preamplifiers between which the signal is demultiplexed to 10 Gbit/s by an $LiNiO_3$ modulator. The demultiplexed data is then detected by a photodiode. All the detected channels had BERs $< 3 \times 10^{-13}$.

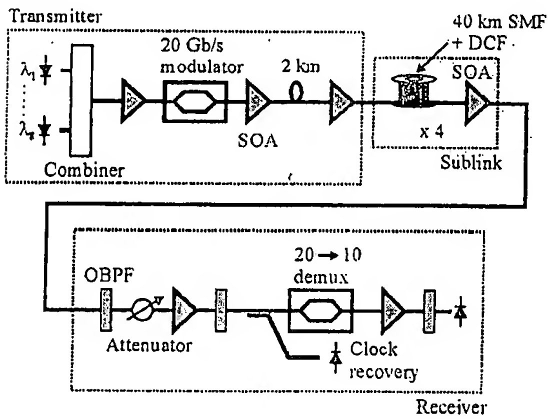

Figure 7: 8-channel WDM transmission experiment. DCF: Dispersion compensating fibre ([2]).

4. SOA nonlinearities.

SOAs can also be used to perform functions that are useful in optically transparent networks. These all-optical functions can help to overcome the 'electronic bottleneck'. This is a major limiting factor in the deployment of high-speed optical communication networks. Many of these functional applications are based on SOA nonlinearities. The development of photonic integrated circuits (PICs) has made feasible the deployment of complex SOA functional subsystems. Nonlinearities in SOAs are principally caused by carrier density changes induced by the amplifier input signals. The four main types of nonlinearity are: Cross gain modulation (XGM), cross phase modulation (XPM), self-phase modulation (SPM) and four-wave mixing (FWM).

4.a. – Cross gain modulation.

The material gain spectrum of an SOA is homogenously broadened. This means that carrier density changes in the amplifier will affect all of the input signals, so it is possible for a strong signal at one wavelength to affect the gain of a weak signal at another wavelength. This non-linear mechanism is called XGM. The most basic XGM scenario is shown in Fig. 8, where a weak CW probe light and a strong pump light, with a small-signal harmonic modulation at angular frequency ω, are injected into an SOA. XGM in the amplifier will impose the pump modulation on the probe. This means that the amplifier is acting as a wavelength converter.

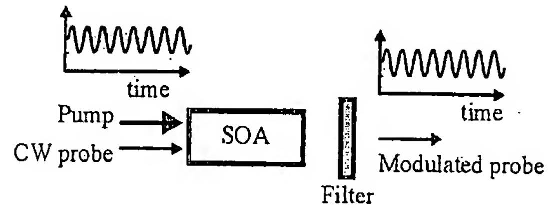

Fig. 8: Simple wavelength converter using SOA XGM.

The most useful figure of merit of the converter is the conversion efficiency, defined as the ratio between the modulation index of the output probe to the modulation index of the input pump. Typical efficiency bandwidths are of the order of 10 GHz.

4.b. – Cross phase modulation.

The refractive index of an SOA active region is not constant but is dependent on the carrier density and so the material gain. This implies that the phase and gain of an optical wave propagating through the amplifier are coupled via gain saturation. This strength of this coupling is related to the linewidth enhancement factor α_l. Plots of α_l versus photon energy are shown in Fig. 9.

If more than one signal is injected into an SOA, there will be cross-phase modulation (XPM) between the signals. XPM can be used to create wavelength converters and other functional devices. However, because XPM only causes phase changes, the SOA must be placed in an interferometric configuration to convert phase changes in the signals to intensity changes using constructive or destructive interference.

4.c. – Four-wave mixing.

Four-wave mixing (FWM) is a *coherent* nonlinear process that can occur in an SOA between two optical fields, a strong pump at angular frequency ω_0 and a weaker signal (or probe) at $\omega_0 - \Omega$, having the same polarisation. The injected fields cause the amplifier gain to be modulated at the beat frequency Ω. This gain modulation in turn gives rise to a *new* field at $\omega_0 + \Omega$, as shown in Fig. 10. FWM generated in SOAs can be used in many applications including wavelength converters, dispersion compensators and optical demultiplexers.

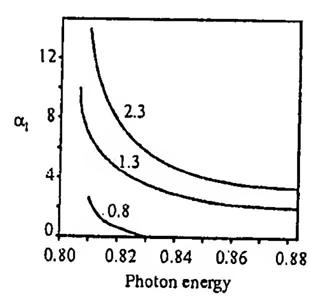

Figure 9: Calculated linewidth enhancement factor versus wavelength for undoped InGaAsP. The parameter is carrier density ($x10^{24}$ m^{-3}) ([3]).

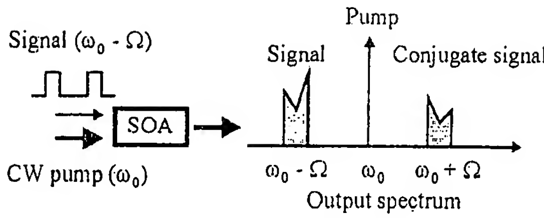

Figure 10: SOA FWM.

5. Functional applications.

5.a. – Wavelength conversion

All-optical wavelength converters will play an important role in broadband optical networks. Their most important function will be to avoid wavelength blocking in optical cross-connects in WDM networks. Wavelength converters increase the flexibility and capacity of a network using a fixed set of wavelengths. Wavelength conversion can be used to centralise network management. In packet switching networks, tuneable wavelength converters can be used to resolve packet contention and reduce optical buffering requirements. We have already seen how XGM in an SOA can be used for wavelength conversion. SOA XPM can also be used for wavelength conversion if SOAs are placed in a Mach-Zehnder configuration as shown in Fig. 11. These wavelength converters have a superior power efficiency compared to those devices based on XGM.

In the asymmetric MZI wavelength converter the CW input at λ_2 is split asymmetrically to each arm of the MZI by a coupler. The intensity modulated signal at λ_1 saturates each SOA asymmetrically inducing different phase shifts in the input CW signal. The output coupler recombines the split CW signals where they can interfere constructively or destructively. The actual state of interference depends on the relative phase difference between the interferometer arms, which relies both on the SOA bias currents and on the input optical powers.

SOA FWM can be used to construct wavelength converters. The basic scheme is shown in Fig. 10, where CW pump and modulated probe input signals are injected into an SOA, generating a new modulated signal. However the conversion efficiency is relatively low for moderate values of frequency detuning between the pump and probe signals. For efficient FWM to occur in an SOA, the polarisation states of the pump and probe must be identical. An example of a more efficient FWM wavelength converter is shown in Fig. 12. In this scheme the input pump is polarised at 45° relative to the polarisation axes of polarisation beam splitter PBS1. This means that half of the pump power is delivered to each SOA along with a co-polarised component of the signal. These mix in each SOA to produce a conjugate signal with the same polarisation. The orthogonal polarised conjugate signals from the SOAs are recombined at the output in polarisation beamsplitter PBS2. If the SOAs have the same gain and conversion efficiencies then the scheme will be polarisation independent.

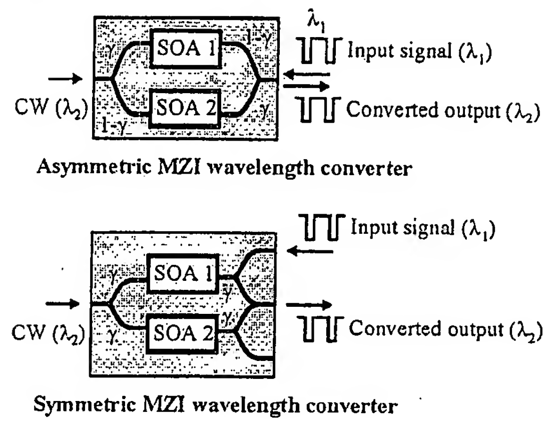

Fig. 11: Mach-Zehnder interferometer (MZI) SOA wavelength converters.

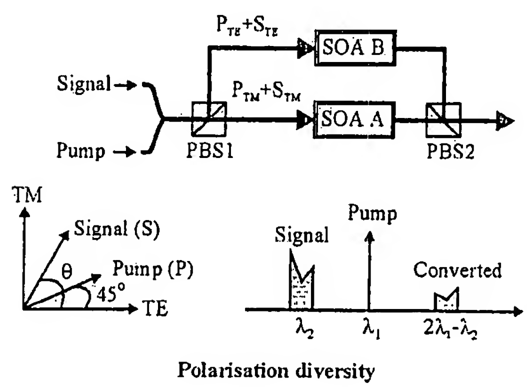

Fig. 12: Polarisation diversity wavelength converter.

5.b. – Optical gates.

Future high-speed WDM and TDM optical communication networks require high-speed optical switches (or gates), that can either be optically or electrically controlled. Such optical switches can be constructed using SOAs. The simplest method to control an SOA gate is by turning the device current on or off. The great advantage of SOA gates is that they can be integrated to form gate arrays. In the 2 x 2 switch module shown in Fig. 13, an incoming data packet can be routed to any output port by switching on the appropriate SOA.

The switching time of a current switched SOA is of the order of 100 ps. Much faster switching times can be achieved using SOAs placed in non-linear loop mirrors (Fig. 14). Switching is achieved by placing an SOA offset from the centre of an optical fibre loop mirror and injecting data into the loop via a 50:50 coupler. The two counter-propagating data pulse streams arrive asynchronously at the SOA. A switching pulse is timed to arrive after one data pulse but just before its replica. The switching pulse power is adjusted to impart a phase change of π radians onto the replica, so the data pulse is switched out when the two counter-propagating components interfere on their return to the coupler. This device is also known as a TOAD (terahertz optical asymmetric demultiplexer) because it can also be used to demultiplex high-speed TDM pulse streams.

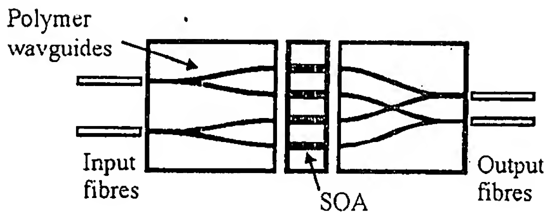

Fig. 13: 2 x 2 hybrid SOA switch module.

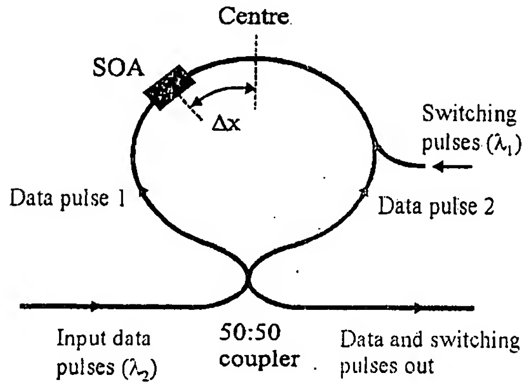

Fig. 14: Optical switch using a TOAD.

5. c. – Optical logic.

Optical logic can be useful for all-optical signal processing applications in high-speed optical networks. Three SOA configurations that can be used to realise optical logic gates are shown in Fig. 15.

5. d. – Multiplexers.

Optical time division demultiplexers (OTDDMs) and add/drop multiplexers (ADMs) are key components required by optical time division multiplexed (OTDM) network nodes. In an ADM one channel is dropped from an incoming TDM data stream leaving the other channels undisturbed. A new channel can be added by inserting data pulses into the vacant time slot.

MZI switches incorporating SOAs can also be used as ADMs. Many configurations are possible, one of which is shown in Fig. 16. In this configuration the input data signal at 40 Gb/s is split into two drive signals. One of the drive signals is delayed by a half a bit period. The interferometer is configured such that when an undelayed signal pulse is present in the upper arm of the interferometer an input 10 GHz pulse is directed to the drop port. At the same time the 3 x 10 GHz pulse stream is directed to the through port. When the delayed signal pulse is present in the lower arm of the interferometer the data is directed away from the drop port. The amplitudes of the drop and through pulses are modified by the SOA gain saturation induced by the input data pulses so pulse amplification and reshaping also occurs, i.e. the device functions as a 2R regenerator. If it is combined with optical clock recovery for retiming it will function as a 3R regenerator. Data can be added to the vacant time slot in the output data simply by sending the add channel data pulses to the add port.

The ability to add and drop wavelength channels in WDM networks is useful for wavelength routing. The function of a wavelength ADM is to separate a particular wavelength channel without interference from adjacent channels. This can be achieved by a wavelength demultiplexer or by using an integrated SOA with a

5

tuneable filter as shown in Fig. 17. The filter can be tuned by changing its current. The selected wavelength channel is reflected by the filter, amplified a second time by the MQW section and extracted to a drop port using a circulator. The remaining channels pass through the filter section to which it is a simple matter to add a new wavelength channel.

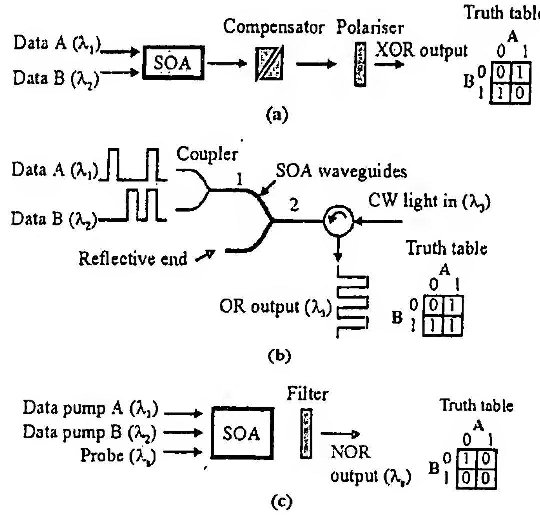

Fig. 15: SOA logic gates, (a) XOR gate, (b) OR gate, (c) NOR gate.

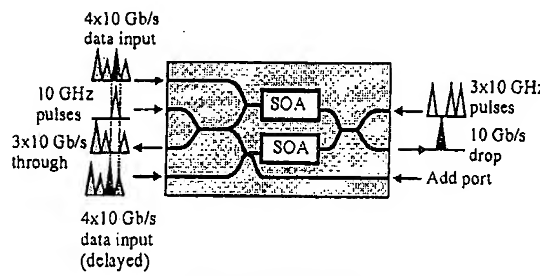

Fig. 16: MZI ADM.

5. e. – Optical pulse generator.

High repetition-rate wavelength tuneable pulses are required in high-speed OTDM WDM communication links. At high frequencies (> 10 GHz) it is difficult and expensive to generate such pulses by electronic means. One optical technique is to use a mode-locked fibre ring laser incorporating an SOA as shown in Fig. 18.

The Fabry-Perot laser is gain-switched by sinusoidal modulation at 10 GHz. After transmission through 150 m of high dispersion fibre each spectral mode in the gain-switched pulses is delayed by 25 ps with respect to its nearest mode. So each dispersed pulse creates a sequence of pulses of *different* wavelengths separated by 25 ps, giving an effective repetition rate of 40 GHz. The pulses can be converted to pulses of the same (tuneable) wavelength by using a fibre ring laser with an SOA as the active element. The 40 GHz optical pulse stream is inserted into the ring by a circulator, causing the gain of the SOA to be optically modulated. This mode-locks the laser. By choosing an appropriate modulation frequency of the laser, 10.188 GHz, it is possible to mode lock the laser at 40.752 GHz (the 3310th harmonic of the ring fundamental frequency). The output

wavelength of the fibre laser is selected using a fibre Fabry-Perot filter. The output power is coupled from the fibre ring using a fibre coupler.

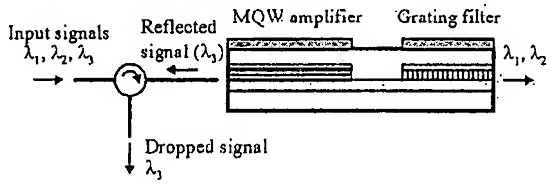

Fig. 17: Tuneable SOA-filter wavelength ADM.

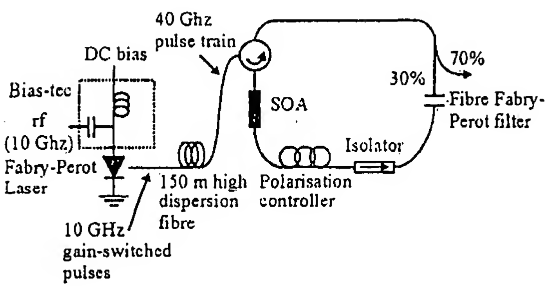

Fig. 18: Optical pulse generation using a mode-locked fibre ring laser incorporating an SOA.

5. f. – Optical clock recovery.

In OTDM systems, clock recovery is required in optical receivers and in 3R regenerators. At high speeds clock recovery is best achieved using an optical solution. An SOA technique (Fig. 19) uses a phase locked loop with an SOA based interferometric switch. In this configuration the OTDM data signal is coupled to the SOA loop mirror, which is driven by an optical control pulse train generated by a tuneable mode locked laser (TMLL), whose repetition frequency is determined by a voltage-controlled oscillator (VCO). The output signal from the loop mirror is detected by a slow photodiode. A fraction of the input signal is switched from the loop mirror at the repetition rate of the control pulses. When the VCO frequency is equal to the base frequency of the input signal, the switched components of the input signal have constant phase within a time slot. In this case the output signal from the photodiode becomes a DC signal whose amplitude is proportional to the phase difference between the input signal pulses and control pulse train, i.e. the optical switch acts as a phase comparator. However this error signal only has a single polarity so there is no discrimination between negative and positive phase differences. This problem can be overcome by detecting the signal using a second slow photodiode. The output signal from this photodiode is subtracted from the error signal. The resulting signal is sent to the VCO via a low-pass filter. This closes the loop and locks the VCO frequency to the base frequency of the input data signal. The optical clock pulses can then be extracted from the output of the TMLL using a coupler.

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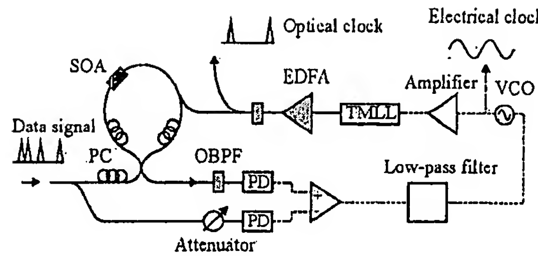

Fig. 19: Optical clock recovery using an opto-electronic phase locked loop and interferometric SOA switch, PD: photodiode, TMLL: tuneable mode locked laser, OBPF: optical bandpass filter, PC: polarisation controller, VCO: voltage controlled oscillator.

6. Conclusion

SOA technology is capable of realising many of the all-optical functions required in emerging optical networks. As optoelectronic integrated circuit technology advances and manufacturing costs fall, the use of SOAs as basic amplifiers and as components in functional subsystems will expand.

7. References.

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